"DAMAGE TO SOLIDS CAUSED BY CAVITATION"

for presentation at

Royal Society Discussion on Deformation of Solids Due to Liquid Impact

London, England, May 27, 1965

Frederick G. Hammitt*
Department of Nuclear Engineering
The University of Michigan
Ann Arbor, Michigan

03424-26-I

* Professor, Department of Nuclear Engineering, University of Michigan

ACKNOWLEDGEMENTS

The work herein reported was supported by NASA (Grant NsG-39-60) and NSF (Grant G-22529), as well as by internal funds of The University of Michigan.

In addition the writer wishes to thank all the various personnel of the laboratory for their assistance in the work on which this paper is based, and particularly Mr. M. John Robinson, Assistant Research Engineer, for his additional assistance in preparing the paper itself.

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

CAVITATION DAMAGE PAPER FOR CAMBRIDGE DISCUSSION

"DAMAGE TO SOLIDS CAUSED BY CAVITATION"

I. INTRODUCTION

This cavitation session covers the full range of cavitation damage from theoretical bubble dynamics to Practical Aspects of Cavitation. My position in the program and general assignment of topic being midway between these extremes, I will consider the present state of research aimed toward predicting cumulative damage or rate of damage for a given prototype flow situation from laboratory experiments or, better yet, basic theory. In spite of much effort over the years, neither of these objectives has been attained, or appears easily attainable. Although the former is difficult, the latter is more so, and has been discussed already today. Hence, I will restrict myself to problems arising from laboratory experiments, and will cover what I consider some of the more significant facts and hypotheses which have been established, and some of the peculiarities which have become evident from various laboratory test results. I will, no doubt, tend to emphasize our own observations over the last several years, since I am most familiar with these. However, I am becoming convinced that cavitation is a phenomenon having many facets, various of which tend to become emphasized depending upon the type of facility and test one is observing.

The laboratory with which I am associated at The University of Michigan has been engaged in cavitation damage research for about five years. The equipment in use includes two small, high-speed, tunnel-venturi facilities, one using water and one mercury, and a 20 kc vibratory unit which has been operated with water, mercury, and lead-bismuth alloy.[1,2]

We have felt that the major objective of such research was to attain a position whereby an a priori prediction of the damage to be expected in a prototype facility would be feasible. We feel that this can best be accomplished using a flowing-system, wherein the conventional fluid-flow parameters of pressure, velocity, and temperature can be measured, and have a meaning similar to that in a prototype machine as a pump, turbine, etc. The flowing system should present as simple a flow-regime as possible so that results can be interpreted with some generality, and its operation should be feasible over a broad range of fluids, temperatures, and velocities. As a good compromise amongst the various alternatives, we selected a venturi. Damage test specimens could then be inserted into the cavitating region.

We also have constructed a vibratory facility primarily for testing with fluids and/or temperatures unattainable with the tunnel facilities. Since the vibratory facility differs so greatly in its flow regime from ordinary fluid-handling machines, it is difficult to use data from such a facility for predicting damage in a flowing system, for given temperature, pressure, velocity, geometry, etc. However, such data can be used advantageously to compare damage between different material-fluid combinations at a given temperature. A broad comparison between these two widely-differing devices will hopefully be attained since the same materials, fluids, and temperatures are being used in numerous cases. However, the present paper is concerned mainly with the venturi devices, since these are more closely related to flow machinery.

II. SIGNIFICANT FACTS AND HYPOTHESES REGARDING CAVITATION DAMAGE IN FLOWING SYSTEMS

A. General

From our own work over the past several years, various points have come to seem significant to us, regarding the nature of cavitation damage, at least in a venturi, and presumably also in other flowing systems. Fig. 1 shows the basic designs of cavitating venturis we have used. They have differed only in the circumferential arrangement of damage specimens, and in the material of construction, i.e., plexiglas and stainless steel.

B. Single-Event Pitting

1. In the early phases of damage we observed two types of pitting, interpreted as follows:

(a) "Crater" pits*, which, because of their symmetry

---

* Among the earlier published observations of such pits are those by Knapp in a water tunnel[3] and in a hydraulic turbine passage.[4] More recently, in addition to our own observations[5,6]; a similar type of pitting has been reported by Varga[7] on lead in a tunnel test, and by Wood on stainless steel in a centrifugal pump.

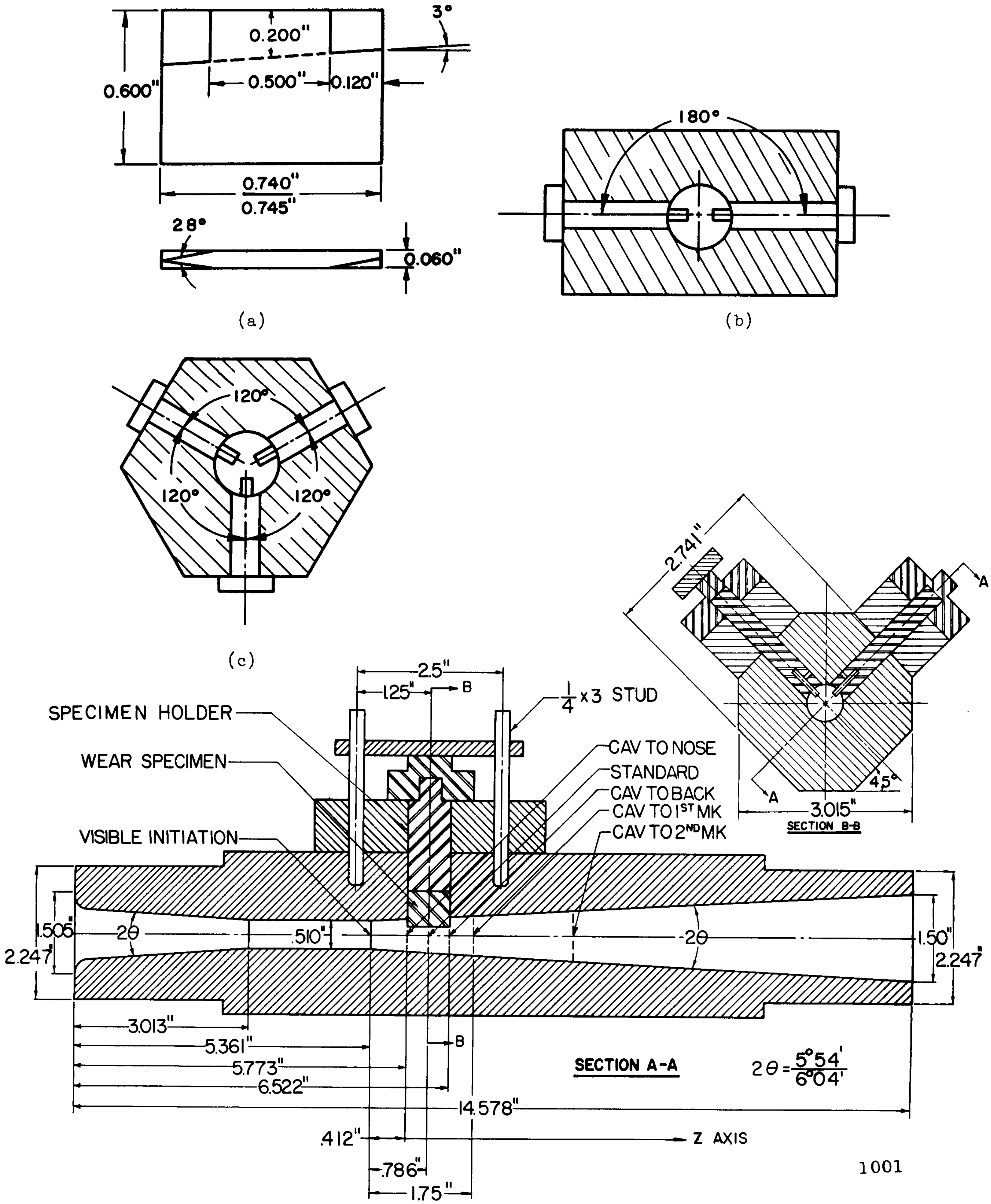


FIGURE 1: Drawing of Damage Test Venturis Showing Nominal Flow Passage, Location and Different Geometry of Specimen Insertions, Specimen Holders, Cavitation Termination Points, and Spceimen Dimensions

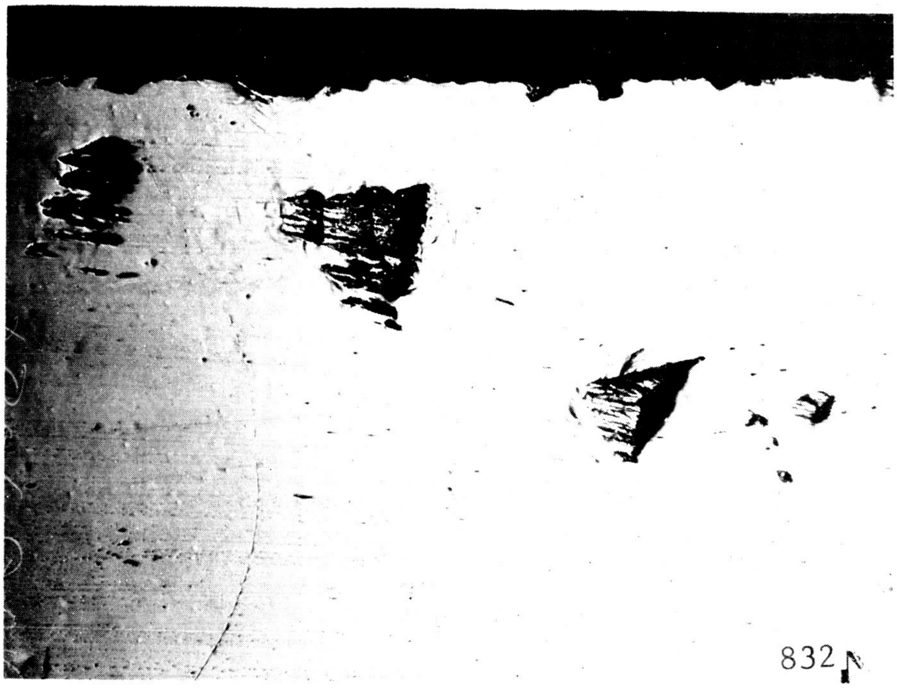
and general appearance, are presumably formed by a single bubble implosion. The traditional mechanism for the imposition of damaging forces on such a surface is through the radiation of shock waves from a bubble collapse and/or subsequent rebound. A competing mechanism which has been suggested[9,10] is that of the impact of a liquid jet formed during the collapse. However, the present observations cannot assist in the choice between these or other mechanisms.

(b) Local fatigue failure, i.e., irregularly-shaped shallow pits, presumably caused by repeated loadings from less energetic bubbles. These are presumed to be also single-event failures, since the size and shape of the pits do not change with subsequent testing.

Fig. 2 and 3 comprise two series of photomicrographs showing both "crater" and "fatigue-type" pits after an initial test duration, and then again after considerable additional testing. The fact that neither their shape nor their depth profile (as shown by detailed "proficorder"* tracings[5] change during additional testing, is taken as strong evidence that these pits are indeed "single-event" failures.

---

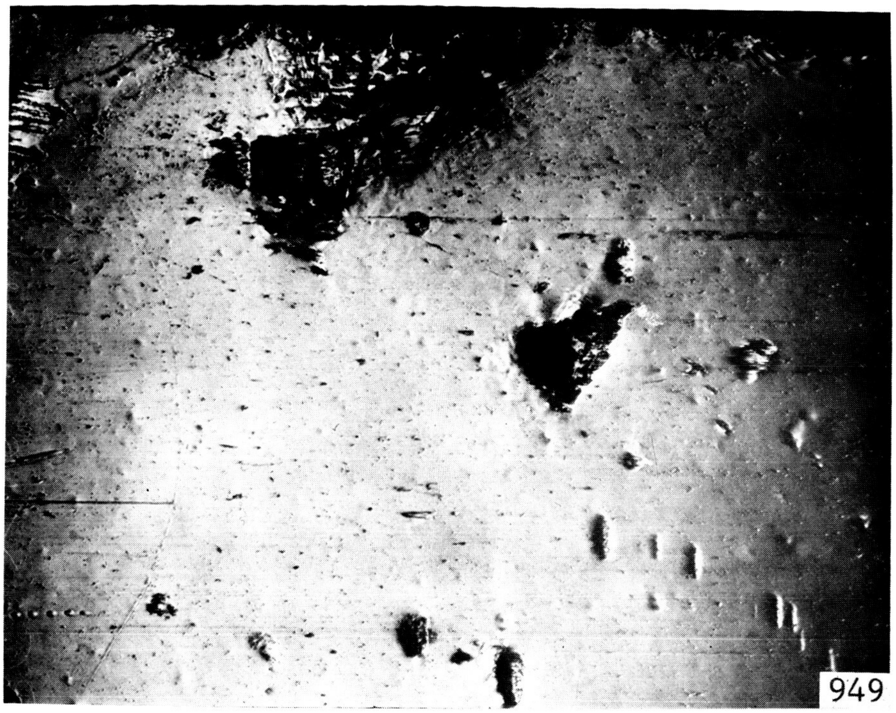
* "Linear proficorder", Micrometrical Division, The Bendix Corporation, Ann Arbor, Michigan



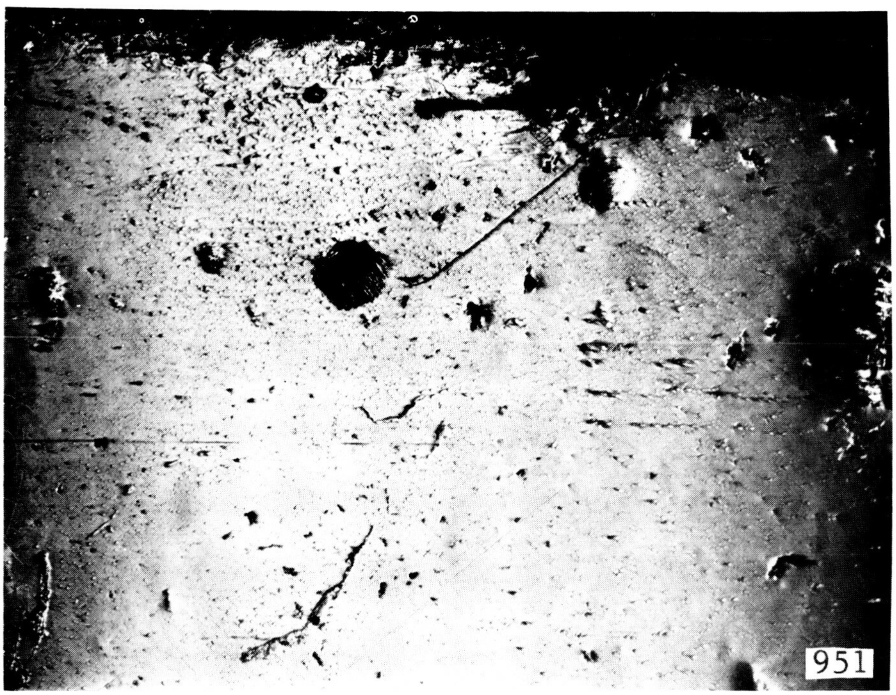
(a)

(b)

FIGURE 2. Development of Cavitation Damage at Two Locations on 302 Stainless Steel Specimen with Water,(a) 15 hrs, (b) 30 hrs.



(a)



(b)

FIGURE 3. Development of Cavitation Damage at Two Locations on 302 Stainless Steel Specimen with Water, (a) 150 hrs, (b) 150 hrs. Same Locations as shown in Figure 2.

The "crater-type" pits caused (in most of the cases which were examined) by room temperature water on stainless steel, typically had a depth to diameter ratio between 15 and 40. However, Fig. 4 shows a microsection of a crater incurred in Cb-1Zr alloy by room temperature mercury with depth to diameter ratio of about 4, showing the effect of a possibly larger force imposition on a somewhat weaker material. Also, crater-type pits of a large depth to diameter ratio have recently been observed on stainless steel in a centrifugal pump test in a high-temperature alkali metal.[8] Assuming that the forces from such alkali metal and from room-temperature water may be roughly similar, but that the mechanical properties of the stainless steel are considerably reduced at elevated temperature, these observations may not be inconsistent. Hence it may be reasonable to expect that the depth to diameter ratio will be a function of the fluid, material, and flow conditions.

In the venturi tests, it has generally been observed that a ridge is raised around the craters, of a considerably smaller height than the crater depth, and, in the great majority of cases observed (about 90 percent), predominently on the downstream side of the crater. Fig. 5 is a proficorder trace of such a crater. The explanation for this non-symmetry of the ridge is not known at present, but the very existence of a ridge suggests that the craters are formed by single-bubble implosions.

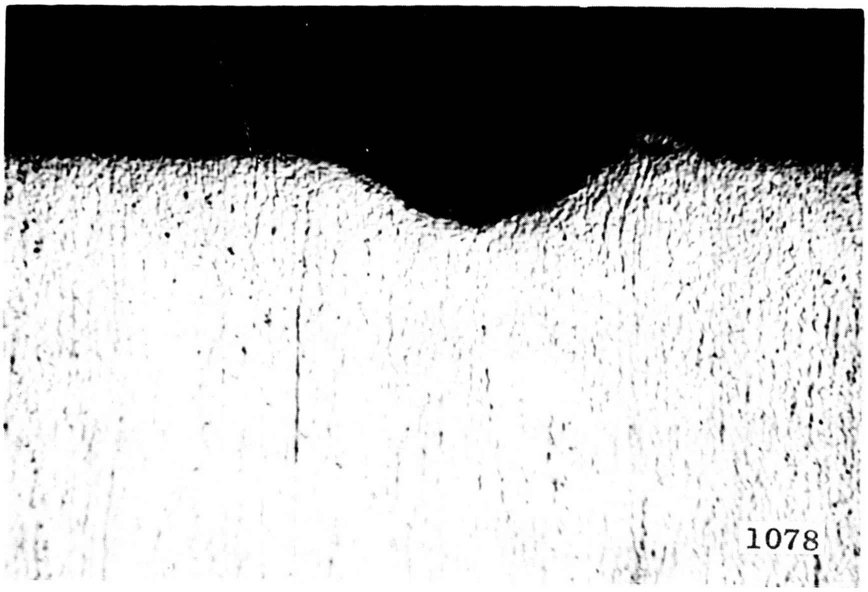


FIGURE 4: Microsection Through Cavitation Pit, (Shown in Figure 8) for "Nose" Cavitation in Mercury at a Throat Velocity of 48 feet/second, Duration 50 Hours. Material is Columbium-1% Zirconium. Etched. Magnification - 1000X

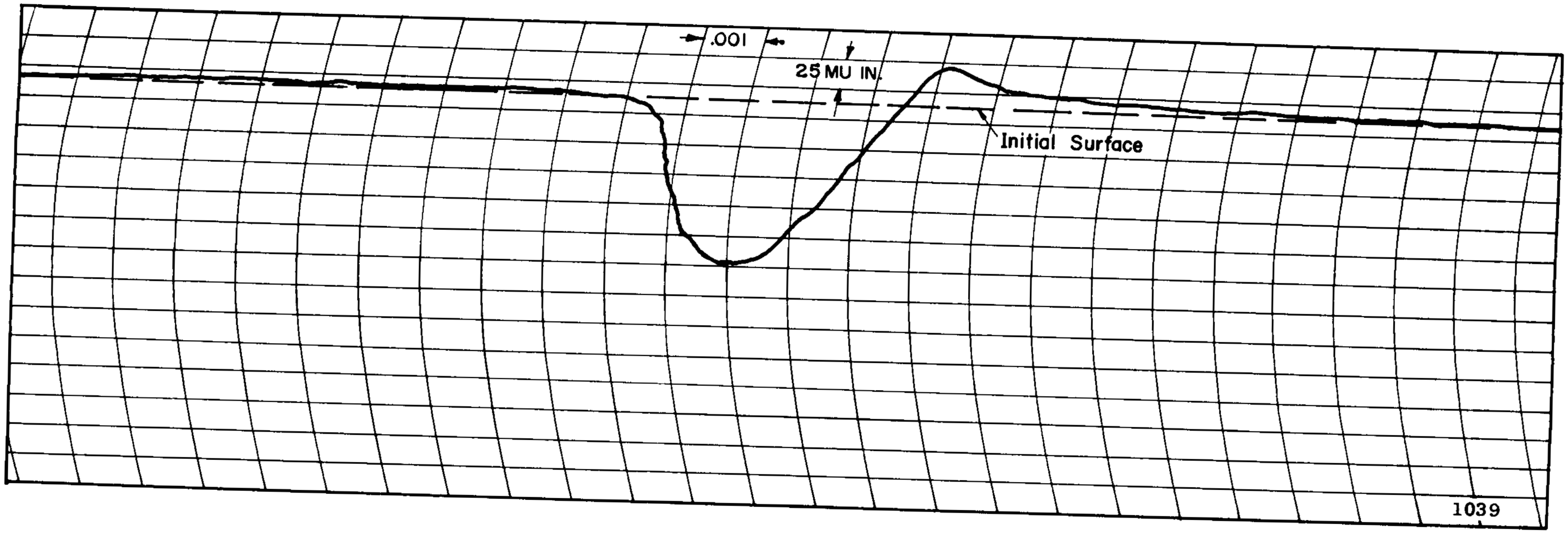


FIGURE 5: Typical Proficorder Trace of a Cavitation P.T. Vertical Scale 25 microinches/division. Horizontal Scale: 0.001 inches/Division

Fig. 6 shows a relatively large crater, as well as numerous smaller pits of both types, formed in stainless steel by cavitating mercury in one of the passages of the centrifugal pump used to drive the mercury loop. This, and the previously cited observations by Knapp[4] and Wood[8] indicate at least some similarity between the cavitation phenomenon as observed in the venturi and as it occurs in turbomachinery.

The detailed observations of pitting from the venturi tests suggest that the pitting is locally random, and that in the early phases of damage, the existence of already incurred damage does not affect the location of new pits. Fig. 7, showing typical pitting by mercury on stainless steel, indicates this point. However, as shown by Fig. 8, if pits are large enough, they are capable of causing localized cavitation, and hence, a damage "wake".

In addition the size of pits appears to be random, ranging from relatively large pits (up to about 50 mils, Fig. 6) down to very small pits. The number density of pits increases, as far as our observations are concerned, without limit as the size decreases. These facts suggested[5] a bubble energy spectrum* (Fig. 9), where the ordinate is the number of bubbles, n(E), from those "in the vicinity" of the damage specimen which deliver, upon their collapse, an energy quantum, E, to the

---

* As pointed out by A. Thiruvengadam in his discussion of reference 5, there is also a spectrum of energy <u>absorbed</u> by the material, which may of course differ from the <u>spectrum</u> of energy <u>delivered</u> by the bubbles.

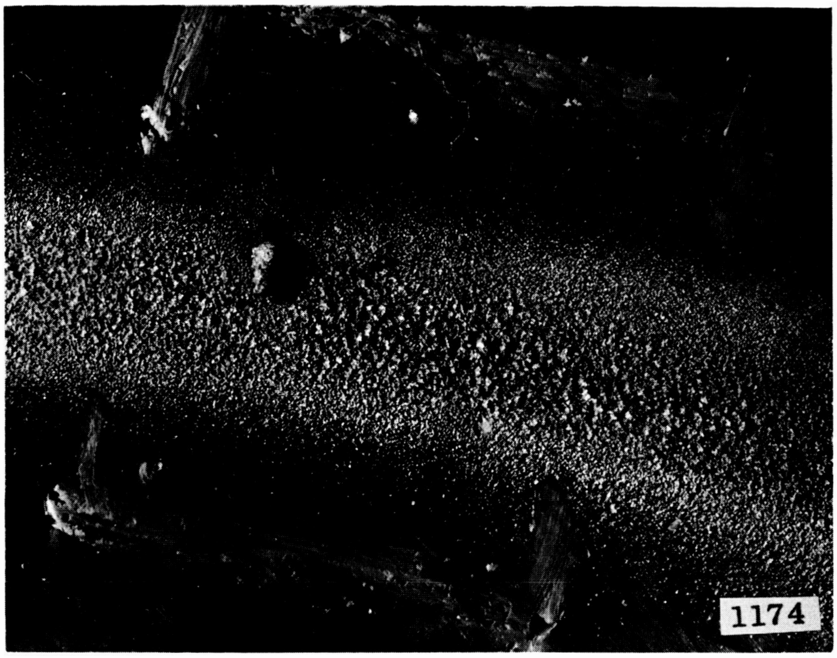


FIGURE 6: Cavitation Damage on Back Shroud of Two Piece Impeller After 596 Hours Exposure to Cavitating Flow in Mercury Magnification 6X

FIGURE 7: Typical Cavitation Pitting from "Visible Initiation" Cavitation in Mercury at a Throat Velocity of 34 feet/second at a Duration of 57 Hours. Sample No. 50-3, Material; Stainless Steel, Magnification; 120X

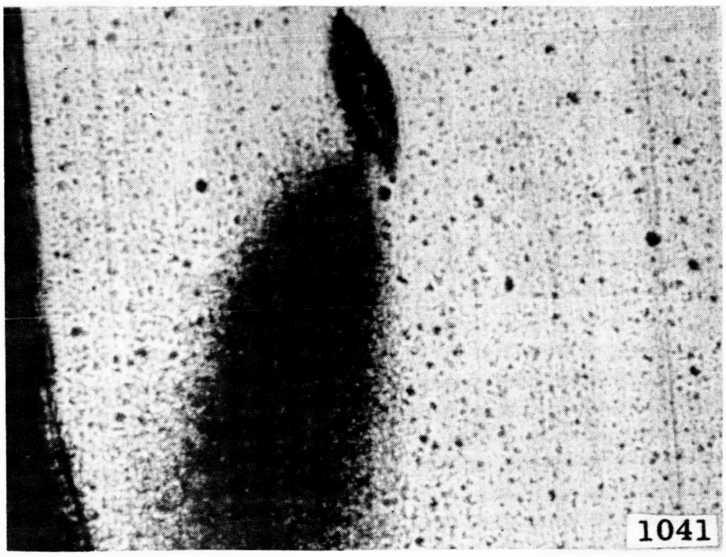


FIGURE 8: Cavitation Pitting in Columbium-1% Zirconium After 50 Hours Exposure to "Nose" Cavitation in Mercury at a Throat Velocity of 48 feet/second. Magnification 120X

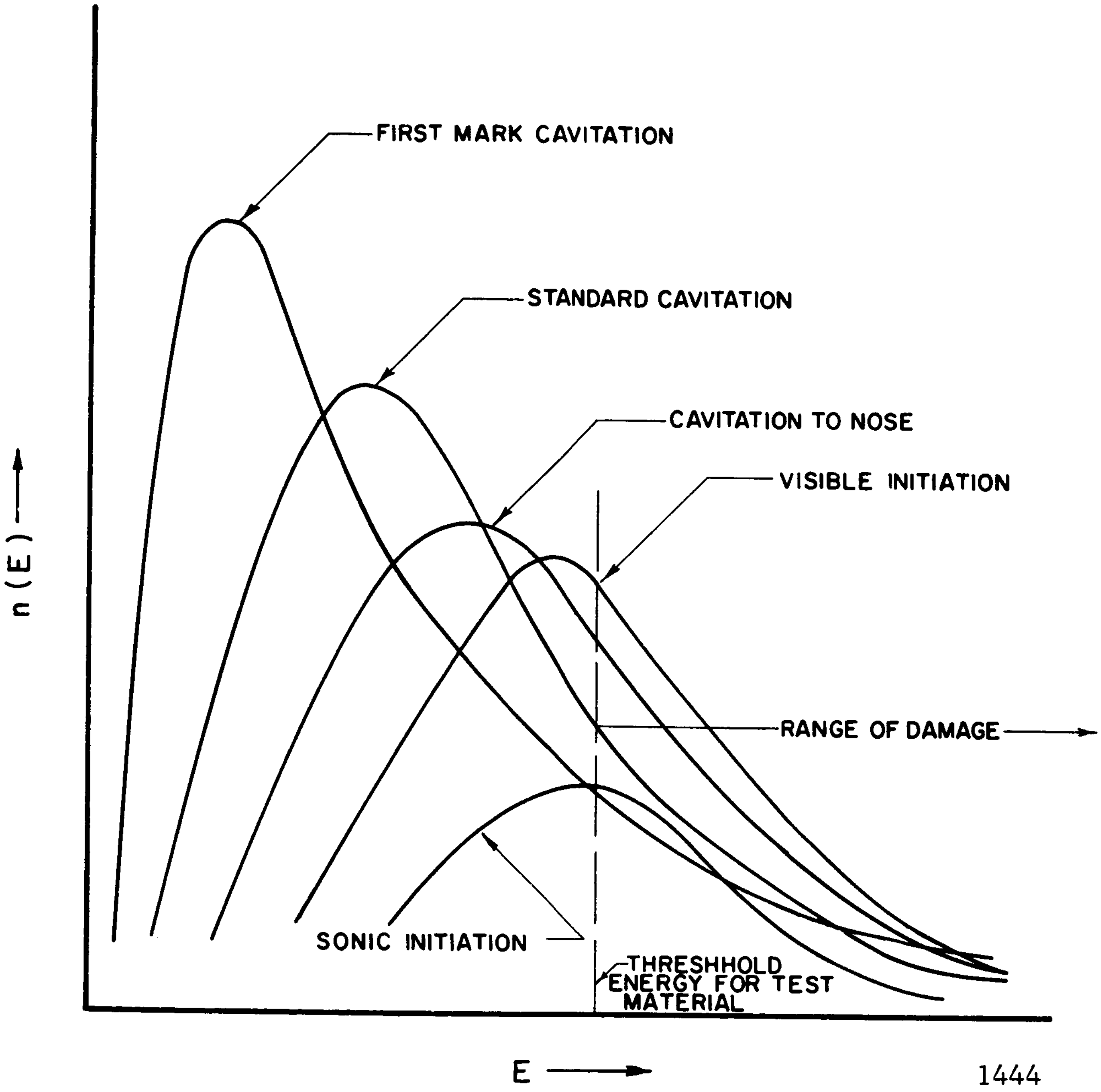


FIGURE 9: Hypothesized Bubble Energy Spectra for Various Cavitation Conditions at a Constant Velocity for a Given Material

surface. As indicated by Fig. 9, for the particular case of a cavitating venturi, the number of bubbles will increase as the "degree of cavitation" is increased* but their mean energy, and hence capability of causing damage, will decrease. A hypothesized threshold damage energy for a given material is shown on the figure.

The randomness of the pitting is taken further to indicate that no "incubation period" exists for crater-type pits, if the method of observation is sufficiently precise, i.e., craters are as likely to occur in the first instant of testing as in any other, and no preconditioning of the surface is required for such pits. This has been verified not only by the pitting observations, but also by the use of an irradiated test specimen[11], which showed a weight loss starting from essentially zero time (Fig. 10). In addition our detailed surface measurements[12] indicate that material is indeed removed from crater-pits. Possible mechanisms, typically considered for removal of material by liquid impact[13,14] are metallic "splash" due to the highly transient nature of the surface loading, or "wash-out" due to high transverse velocities.

The fatigue-type pits do suggest an "incubation period", but only for that specific mechanism. Thus for a system where this phenomena was predominant, an incuba-

---

* The labeling of the curves is as explained in ref. 5, but generally shows an increase in the extent of the cavitating region as one moves away from the "sonic initiation" and "visible iniation" curves.

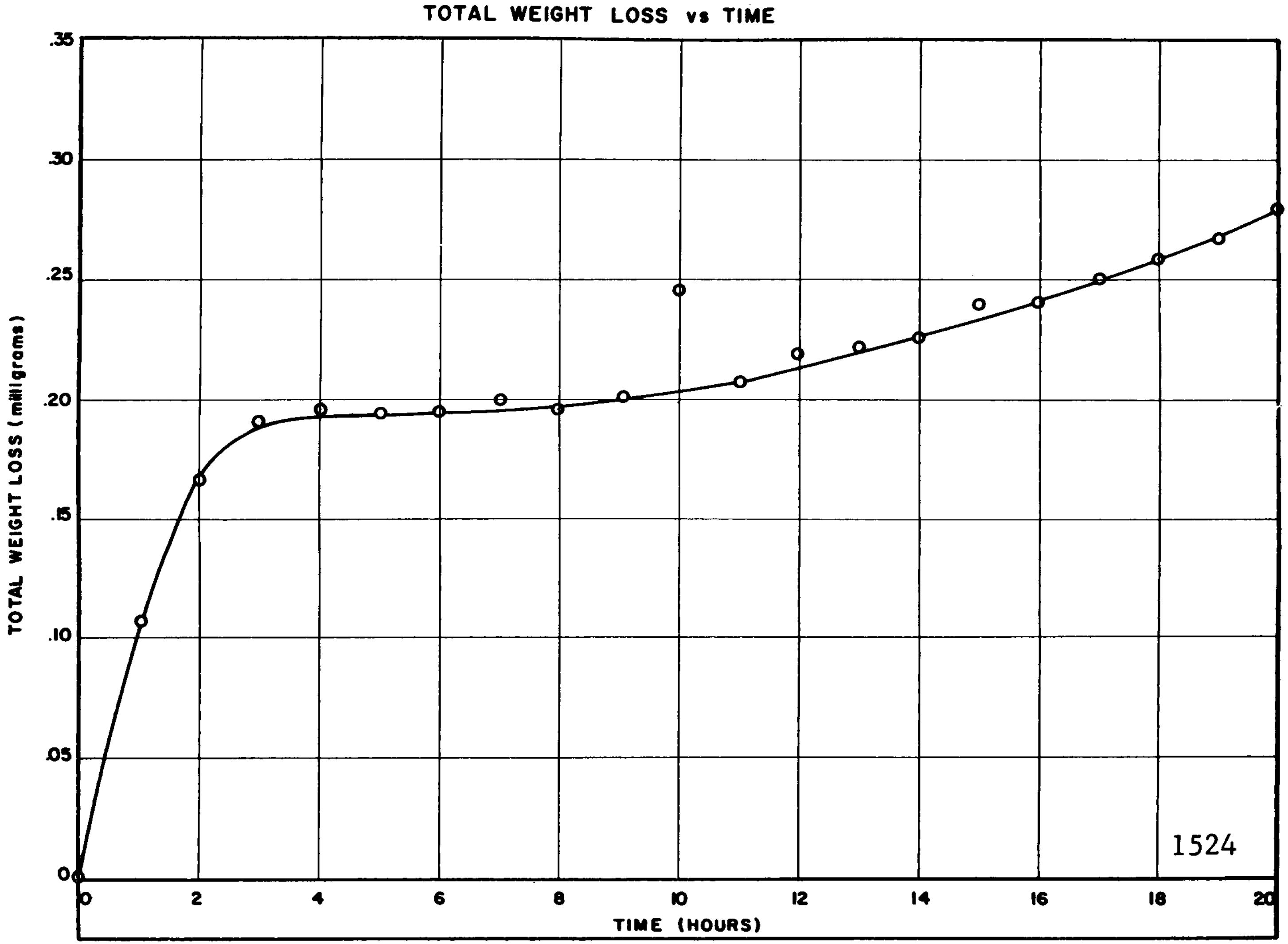


FIGURE 10: Total Weight Loss versus Duration for Stainless Steel at "Standard" Cavitation in Water at a Throat Velocity of 70 feet/second as Determined by Observations on Radioactive Debris from Irradiated Specimens

tion period could possibly exist.

C. Rate of Cavitation Damage

The venturi tests indicate a highly time-dependent rate of damage[5,6]. Almost uniformly a high initial rate is observed followed by a considerably decreased rate, but then increasing again to subsequent peaks in the rate vs. time curve. This behavior is indicated by the sketched rate curves of Table I for numerous samples tested in mercury[15] as well as by the previously mentioned irradiated specimen curve[11], and by Fig. 11 from (reference 6). We ascribe the early rate peak to surface imperfections, inclusions, or other "weak-spots", rather than to fluid dynamic effects. However, we feel the later non-linearities are primarily due to the perturbations of the local flow pattern by the roughened surface, and to a lesser extent to changes in the surface micro-structure due to work-hardening, etc. We have observed such an increase in micro-hardness in some work-hardenable materials, as may also have been observed elsewhere. Ideally then, a characteristic damage-rate curve for a given type of facility and flow condition, depending only on the state of damage already accrued, would be expected, assuming that ideally all materials "damaged" in such a way that flow perturbations and surface property changes would be similar. Actually, however, this simplified model does not appear to be realistic.

D. Sensitivity to Minor System Variations

TABLE 1

MEAN DEPTH OF PENETRATION FOR SPECIMENS AT SELECTED DURATIONS FOR MERCURY

Spec. No.	Mat'l.	Hg Cond.	Vel. ft/sec	Cav. Cond.	MDP After X Hours 50	100	200	500	800	Sketch Of Rate Curve
1-3	SS	Cold -Wet	24	Std.	55	70	145			
2-3	"	"	"	"	65	85	180			
11-3	"	"	34	Zero	0					
12-3	"	"	"	"	0					
53-3	"	"	"	"	0(10 hr)					
55-3	"	"	"	"	0(10 hr)					
49-3	"	"	"	Vis.	3	6				
50-3	"	"	"	"	2	3.5				
84-3	"	"	"	"	3.5(25 hr)					
99-3	"	"	"	"	0.5(25 hr)					
63-3	"	"	"	Nose	4	5				
64-3	"	"	"	"	6	6				
107-3	"	"	"	"	0.4(25 hr)					
113-3	"	"	"	"	3 (25 hr)					
64-1	CS	"	"	"	130	300				
65-1	"	"	"	"	80	280				
22	CbZr	"	"	"	42					
23	"	"	"	"	67					
6-3	SS	"	"	Std.	55					
7-3	"	"	"	"	55					
47-3	"	"	"	"	40	100	130	650	730	
48-3	"	"	"	"	60	150	180	530	600	
71-3	"	"	"	"	17(10 hr)					
78-3	"	"	"	"	78					
112-3	"	"	"	"	47					
81-3	"	"	"	"	36					
82-3	"	"	"	"	47					
87-3	"	Dry-Cold	"	"	3.0					No data

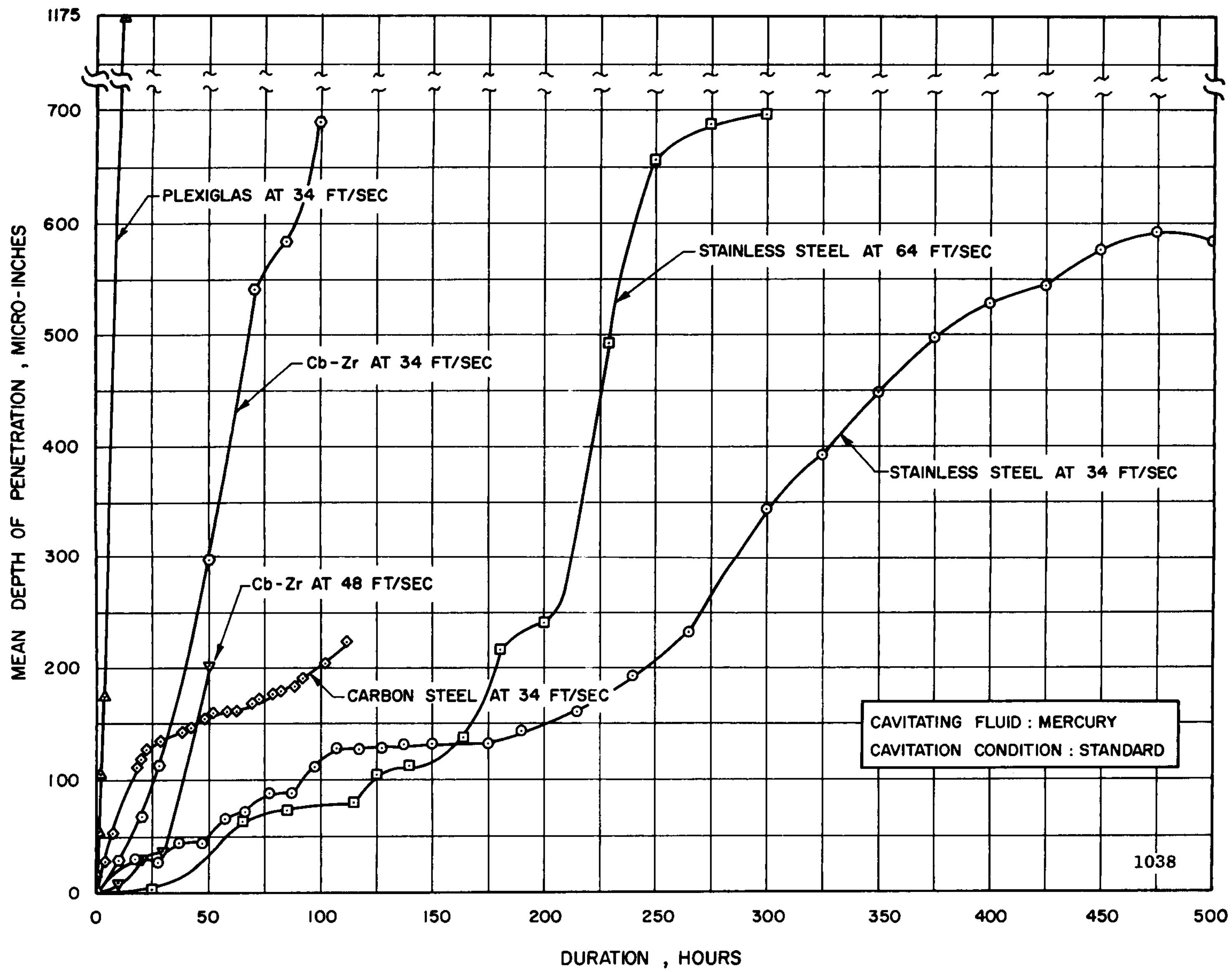
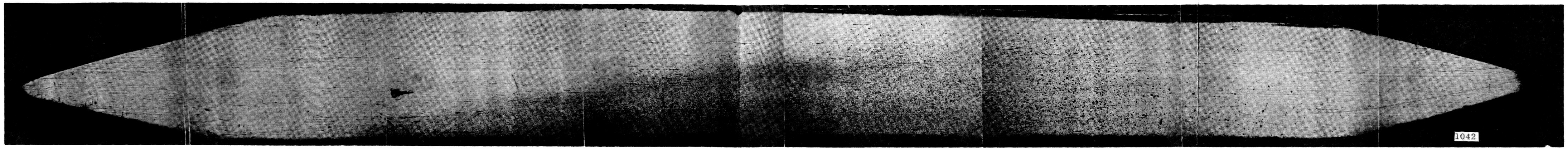


FIGURE 11: **Mean Depth of Penetration vs. Time for Various Materials and Velocities in Mercury**

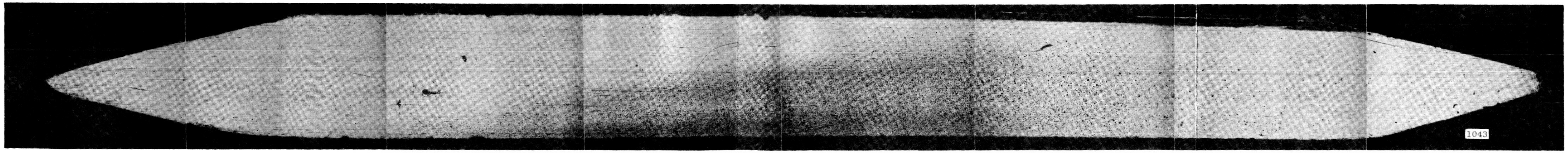
In conformity with my impressions of operating experience in prototype machinery, we have found that the rate of cavitation damage for a given flow system, geometry, fluid-material combination, temperature, velocity, and overall "degree of cavitation" can be changed by an order of magnitude by apparently minor system variations. Our investigations in this respect are not complete. However, among the variations which we find can have a significant effect in our own facility are the following:

1. <u>Orientation and Number of Test Specimens</u>: Fig. 1 shows the three test specimen orientations which have been used. Of the three, two are symmetrical and the third is not. However, non-symmetrical pitting distributions have been noted[6], wherein the flow has appeared to cross a side-edge of the specimens, coming from the relatively restricted region between the specimens (120° separation side). This is clearly illustrated in Fig. 12, e.g., wherein it appears that the damaging cavitation is that triggered by the flow crossing the sharp edge of the specimen, rather than the general cavitation cloud.

Detailed pressure measurements made along the polished face of a test specimen[15,16] indicate a strong dependence of the specimens. Since it has been observed[6] that the most damage occurs in the regions wherein substantial pressure recovery from the minimum around the nucleation region has already oc-



a



b

FIGURE 12. CAVITATED SURFACE OF STAINLESS STEEL SPECIMEN NUMBER 84-3 FOR "VISIBLE INITIATION" CAVITATION CONDITION IN MERCURY AT A THROAT VELOCITY OF 34 FEET/SECOND.
(a) 6 hours duration, (b) 15 hours duration.

curred*, and since the sharpness and location of the pressure gradient is a function of the specimen arrangement, it would be expected that the specimen arrangement might substantially affect the damage rate.

2. Fluid Purity: It has long been recognized that relatively large quantities of entrained gas may well substantially reduce cavitation damage. It is indicated by the present tests that small quantities of water in mercury may increase damage significantly (even to relatively non-corrodible materials such as stainless steel), whereas larger quantities of water may well reduce it. The very preliminary data of Fig. 13 indicates a maximum damage capability at about 1500 ppm of water in mercury. The effect of small quantities of water is presumed to be through the competing mechanisms of increasing the effective vapor pressure of the fluid, and thus promoting growth and nucleation, while at the same time perhaps cushioning the collapse. It is believed that the effects of small quantities of gas may be somewhat similar. A decrease in damage with increased dissolved gas has been shown for a vibratory test[17], but I know of no further data regarding this effect.

3. Venturi Roughness: For some of the tests, plexiglas venturis have been used. While it has been found that these are quite damage-resistent in water, they damage rapidly in mercury, and received pitting on the order of 1/16" in depth

---

* Electrical conductivity measurements through a microprobe indicate that the fluid is essentially 100% (volume-time mean) liquid at these damaged points.

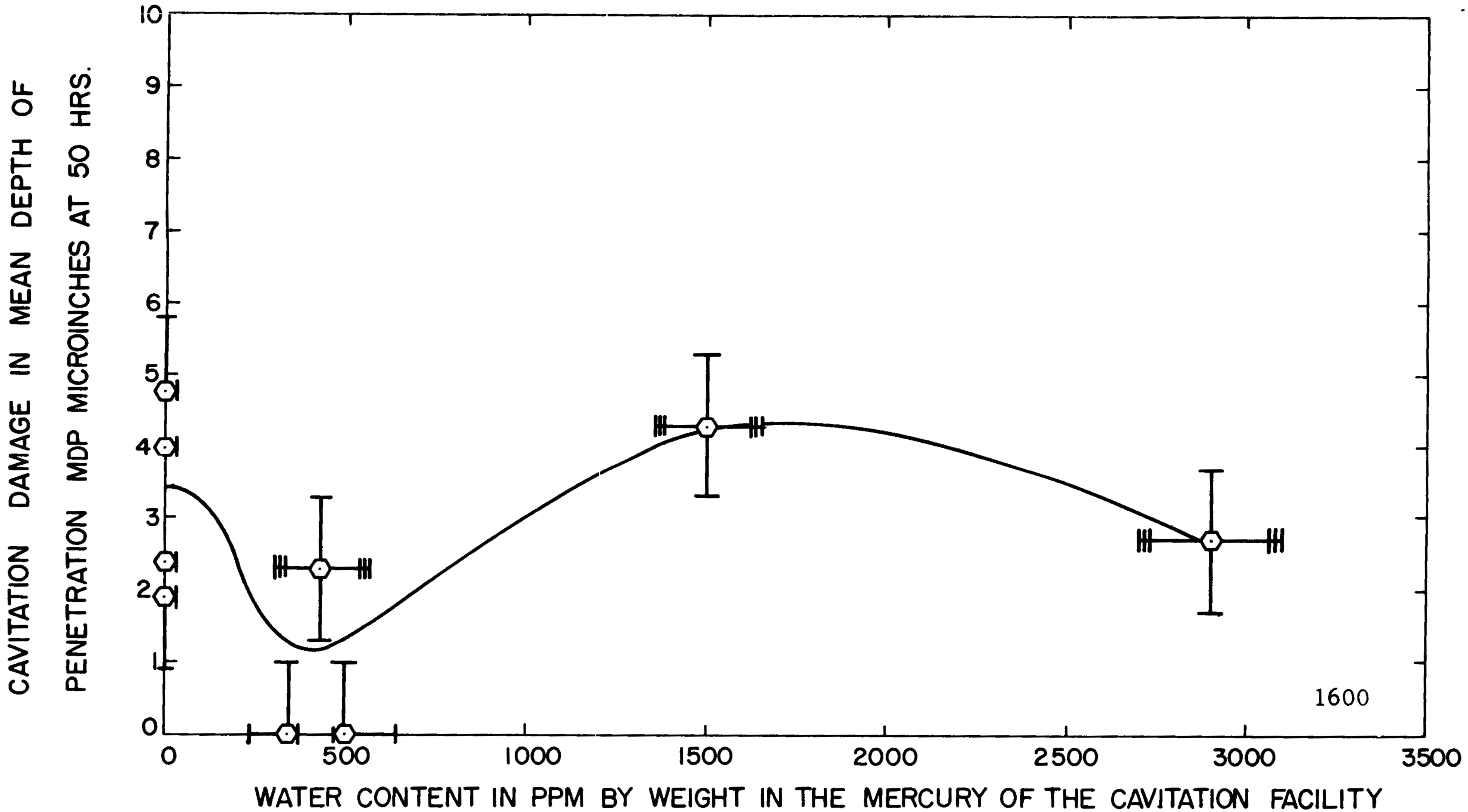


FIGURE 13: Mean Depth of Penetration vs. H_2O Content (in ppm) in Mercury

near the termination of the cavitation region, i.e., just downstream of the test specimens. It appears that damage rates are considerably greater in such damaged venturis, leading to the suspicion that strong vortices must be formed near the trailing edges of the test specimens, and that these cause considerable damage to the specimens. Examination of some of the more heavily-damaged specimens (Fig. 14), where the damage appears concentrated around the trailing-edge (which has actually been reduced substantially in length) tends to confirm this belief.

4. <u>Type of Specimen</u>: In some tests, a small pin-type specimen, positioned across the stream and with axis normal to the flow, has been used in place of the "plate" specimens (Fig. 1) at approximately the same location in the diffuser. The flow conditions have been adjusted so that the cavitation region terminates around the downstream half of the pin. Severe cavitating vortices are thus created adjacent to the pin, and caused to collapse nearby by the strong axial pressure gradient caused by the venturi diffuser. While this is a rather severe "system variation" (from the plate specimens), it causes an increase of damage rate of the order of 300. Fig. 15 is a micro-section through one of the pins in which a hole was eroded in the 20 mil wall in a 5 hour test in mercury.

Somewhat similar damage tests have been previously reported[7,18] in which damage was observed noton the pin, but on lead plates imbedded downstream in the walls of a water tunnel test section.

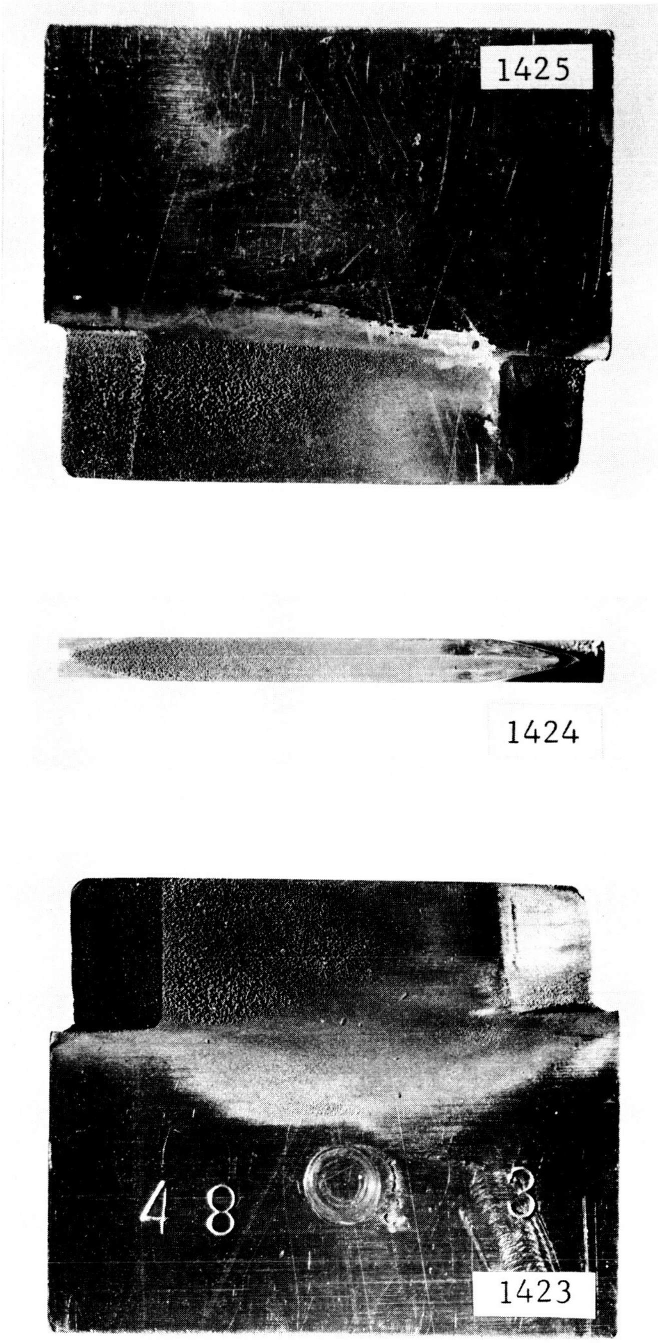


FIGURE 14: Back Side, Polished Surface and Front Side of Specimen No. 48-3 (SS) after 800 Hours Exposure to Cavitation in Mercury at a Throat Velocity of 34 feet/second, for "Standard" Cavitation

FIGURE 15: Metallographic Cross-section Through Stainless Steel Pin Specimen Wall, Magnification 50X

The above indications from a laboratory device strongly support the supposition that apparently relatively minor changes in the geometry or other conditions of a turbomachine can change cavitation damage rates by orders of magnitude. Further, it is indicated that the imposition of vorticity upon an otherwise essentially translatory flow can increase damage potential tremendously. This is supported by the observation of relatively very high damage rates with the pin specimens, as well as by the apparent increase in damage when non-symmetries are introduced into the flow as by the venturi roughness or the specimen orientation. In addition, recent tests on open-shrouded centrifugal pumps indicates that the trailing vortices from upstream blades present a much more severely damaging flow than the relatively translatory flow around the blade leading edges[8].

E. <u>Fluid Velocity Effects</u>

Several previous investigations of velocity effects upon cavitation damage have shown that it increases very rapidly with velocity, approximately as the sixth power of the velocity increment above a "threshold velocity" below which no damage occurs[3]. Though no theoretical justification is available, this approximate relationship has been roughly confirmed in several different types of facilities:

1. Cavitation upon an ogive in a water tunnel[3]

2. Liquid jet impinging upon rotating test specimens[21*]
3. Rotating disc with through-holes as cavitation inducers[19,20]
4. Cavitation behind a pin transverse to flow in a water tunnel[7,18]

Our observations do not confirm the existence of a true threshold velocity, within the velocity ranges for which cavitation can be attained in our facility. We feel that the appearance of such a limiting velocity is to some extent a function of the precision of damage observation, i.e., the more precise the observation the lower the threshold velocity would appear to be. If, for a given experiment, a lower threshold velocity is assumed, the power to which the velocity increment above that threshold must be raised to fit the experimental data (which is usually at best a rough fit), also becomes lower.

In our tests, the velocity exponent, defined as above and based on throat velocity with zero threshold velocity, depends on the "degree of cavitation", since this affects the static pressure profile in the vicinity of the test specimens. The exponent then varies from about zero (or less) to 5 for some tests. In many cases the exponent varies widely over the range tested. Fig. 16 shows typical results for mercury[6]. The "Ca-

---

* The fact that damage from an impinging jet and from cavitation is affected in a manner similar to cavitation damage by velocity, as well as the similar appearance of the pitting, has been taken as an indication that the damaging mechanisms may be the same.

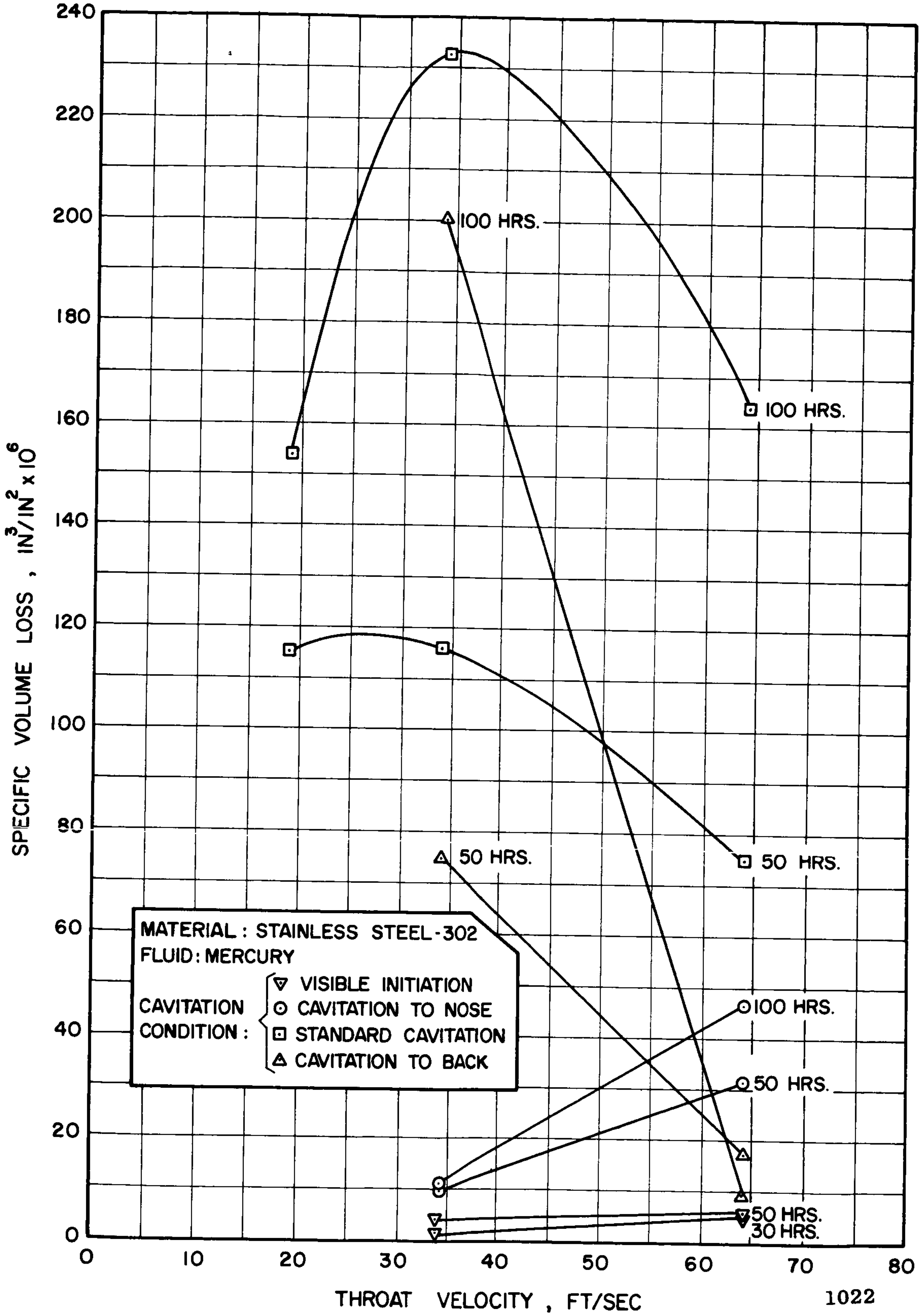


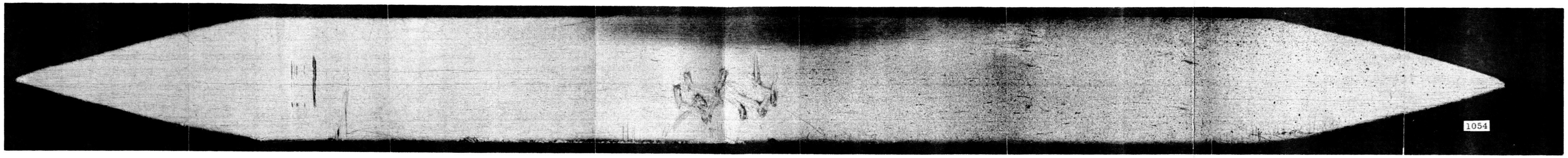
FIGURE 16: Actual Specific Volume Loss vs. Throat Velocity for Constant Time and Various Cavitation Conditions for Stainless Steel in Mercury

vitation conditions" listed in the legend are in increasing order of extent of cavitating region.

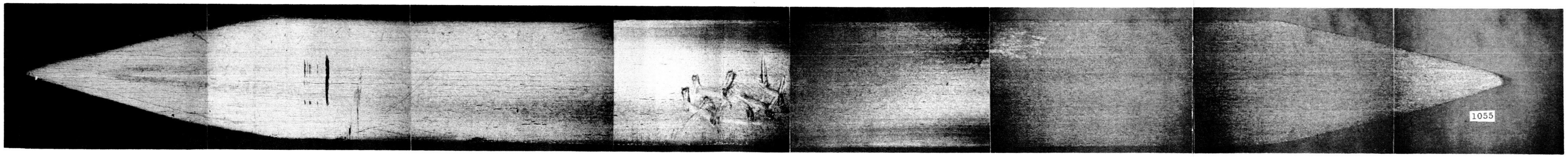
We have explained this behavior in the following manner. For the well-developed cavitation conditions, the entire damage specimen sees essentially vapor pressure at all velocities, and hence the collapse violence is not a substantial function of fluid velocity, leading to the essentially zero damage exponent observed in these cases. For cases where the cavitating region terminates well forward on the specimens, the pressure along the remainder of the specimen is substantially above vapor pressure by virtue of the venturi diffuser. The static pressure, then, over part of the specimen is substantially above vapor pressure by virtue of the venturi diffuser. The static pressure, then, over part of the specimen, is strongly a function of fluid velocity in these latter cases, leading to the higher exponents which are observed. Fig. 17 shows a damage specimen exposed to this type of flow. The distribution and size of pits are consistent with the above explanation. They show a large number of small pits in the regions exposed to low static pressure, and a smaller number of larger pits in the region further downstream where the pressure is higher, i. e., the driving pressure for collapse is greater and only the larger bubbles penetrate the high pressure region, thus causing fewer, larger pits.

F. Prestressing Effects

Since cavitation-erosion involves in many cases a pre-



a



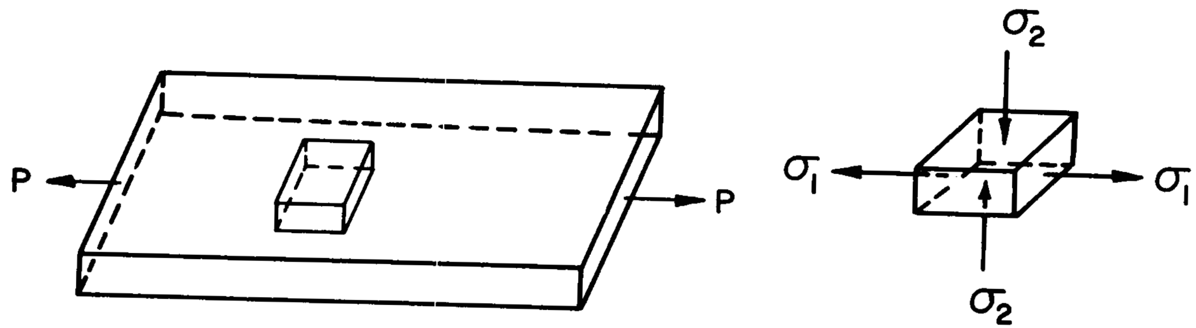
b

FIGURE 17. CAVITATED SURFACE OF STAINLESS STEEL SAMPLE NUMBER 71-3 FOR "STANDARD" CAVITATION IN MERCURY AT A THROAT VELOCITY OF 34 FEET/SECOND. Magnification 37.5X. (a) 6 hours duration, (b) 10 hours duration.

dominently mechanical attack, it is logical to suppose that the rate of damage will be affected by the stress regime existing in the structural member prior to attack. This is a practical consideration because substantial stress levels may well exist in many fluid-flow components, and because it may be possible to inhibit or enhance cavitation damage by a suitable prestressing of the surface.

Fig. 18 shows the presumed state of stress around a cavitation crater, including zones of both tensile and compressive loading. Assuming as a first approximation the maximum shear stress failure mode, the failure criterion becomes the maximum absolute magnitude of the difference between principal stresses. As indicated in Fig. 18, the likelihood of failure under cavitation attack, if it occurs due to excessive tensile load (around the crater rim) will be increased by imposition of a uniaxial compressive load; vice-versa if the failure is due to excess compressive load (in the center of the crater). Hence, cavitation testing of prestressed specimens could shed light on the failure mechanism.

A preliminary series of tests of stainless steel specimens under varying degrees of tensile load (ranging up to 1.3 x the yield strength) has been completed.[22] The specimens were thin plates held across the venturi in the location of the conventional specimens, and loaded by an external clamp. They were so designed that they could be pulled in a tensile machine at the completion of the cavitation test, so that effects upon



$\sigma_{failure} = |\sigma_1 - \sigma_2| < |\sigma_1|$ when σ_2 is tensile

σ_1 = tensile stress due to applied load, P

σ_2 = Normal stress due to hubble implosions

(a)

(b)

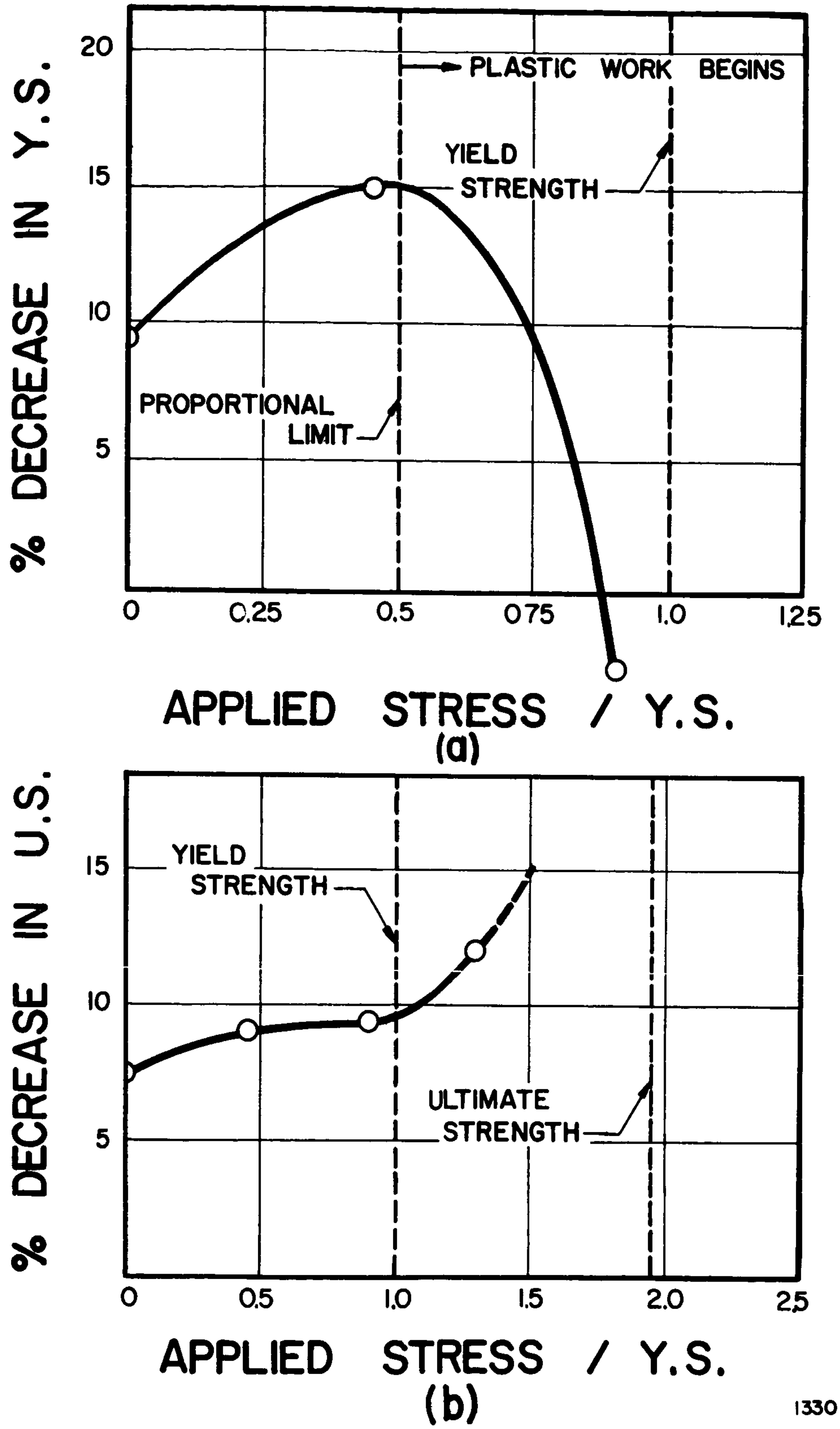
1601

FIGURE 18: Sketch of Possible Stress Distribution Under a Typical Cavitation Pit

the stress-strain curve could be measured.

The following results were obtained from these preliminary tests:

1. The effect of the applied tensile strength on cavitation damage rate was small, although the damage was increased slightly by the larger applied stresses (about 8%).
2. The applied tensile stress in combination with cavitation caused a decrease in ultimate strength which became more substantial as the applied stress was increased (much more rapidly than an estimate based on mean depth of penetration would indicate). The effect is shown in Fig. 19 where the correction to the strengths for changes in damage are negligible. Also as shown in Fig. 19, the yield strength decreased after cavitation for relatively moderate applied loads, but increased for applied loads above the preportional limit, no doubt due to cold-work caused by the applied loads.
3. The effect upon yield and ultimate strengths of a measured mean depth of penetration due to cavitation attack has been measured, and found (for the unstressed specimens) to agree approximately with an estimation based on actual localized depth of penetration as measured from a microsection. An estimate based on mean depth of penetration would, as assumed, seriously underestimate the actual weakening of the specimen. The increased loss of ultimate strength for the specimens cavitated under an applied



(a) Percent Decrease in Yield Strength vs. Applied Stress.
(b) Percent Decrease in Ultimate Strength vs. Applied Stress.

FIGURE 19: Effect of Cavitation Damage vs. Applied Stress on Yield Strength and Ultimate Strength of Stainless Steel

load (and for the yield strength also for applied loads below the proportional limit), above and beyond that estimated from depth of penetration, is thought perhaps to be due to the increased growth of microcracks under the applied load. This hypothesis has not yet been substantiated by actual examination of the specimens.

4. No creep of the specimens under cavitation attack was found even for the maximum applied load.

It is planned to conduct a further series of tests with specimens designed for either compressive or tensile loads, since it is possible that some inhibition of cavitation damage may be achieved by an applied compressive load, and that some information on the actual damage mechanism may be gained.

It is possible that surface treatments to induce compression normal to the surface might be found effective in reducing damage, and it is hoped to investigate this effect also.

H. Material-Fluid Property Damage Correlations

A major objective of cavitation damage research is certainly the determination of a grouping of material, fluid, and flow-parameters which could be used to correlate cavitation damage and hence allow its a priori prediction. For the present, this objective appears to us unattainable in the completely general case. Hence, certain limiting assumptions must be made, as, e.g.:

1. Consideration is limited to a single type of cavitating flow regime, with a single fluid under fixed conditions,
2. only mechanical damage effects are significant (an equally permissible alternative assumption for certain cases would be that only chemical effects were significant. However, the first assumption is more applicable to our venturi tests).

Correlations with various single properties as tensile strength, surface hardness, yield strength, endurance limit, etc. have been suggested by numerous investigators in the past[23,24,25, e.g.] and more recently a possible correlation with strain energy to failure has been emphasized[26,27].

Since the pits we have observed appear to originate from two competing mechanisms, i.e., single-blow cratering and fatigue failure, it is not reasonable to expect precise correlations against a single mechanical property to be possible. While strain energy to failure may conceivably be predominant in determining resistence to loss of material from crater-type pits, resistence to fatigue failure should involve such strength properties as the endurance limit, e.g. A very large number of blows which did not create stresses greater than the endurance limit would not cause failure or any permanent effect even though the strain energy was very low.

In our present opinion, there are two general categories of mechanical properties which are important in this context, i.e., strength properties and energy properties. The first category includes ultimate strength, yield strength, hardness, and endurance limit, all of which, to a first approximation, are more or less proportional, so that which of these is considered is not of primary importance. The second category includes strain energy to failure, impact resistence, or ductility (if a strength property is already considered). Again, which is chosen is of secondary importance.

Both types of properties are significantly involved in most cases of cavitation damage, so that an idealized material of very high strain energy and low strength; or conversely one of very great strength but low energy, would present high resistence to cavitation damage.

For materials such that strain energy increases with strength an increase of either type of property would result in increased cavitation resistence. Stainless steels and various refractory alloys which we have tested are of this type.

On the other hand, for some materials, as strain energy is increased, strength properties decrease. Various Cu-Zn-Ni alloys which we have tested are of this type. The results of these tests (Fig. 20 and 21) confirm these suppositions, and show that a "trade-off" between strength and energy properties in terms of cavitation resistence exists. As noted from these figures, the correlation is about equally good in terms of either tensile strength or strain energy.

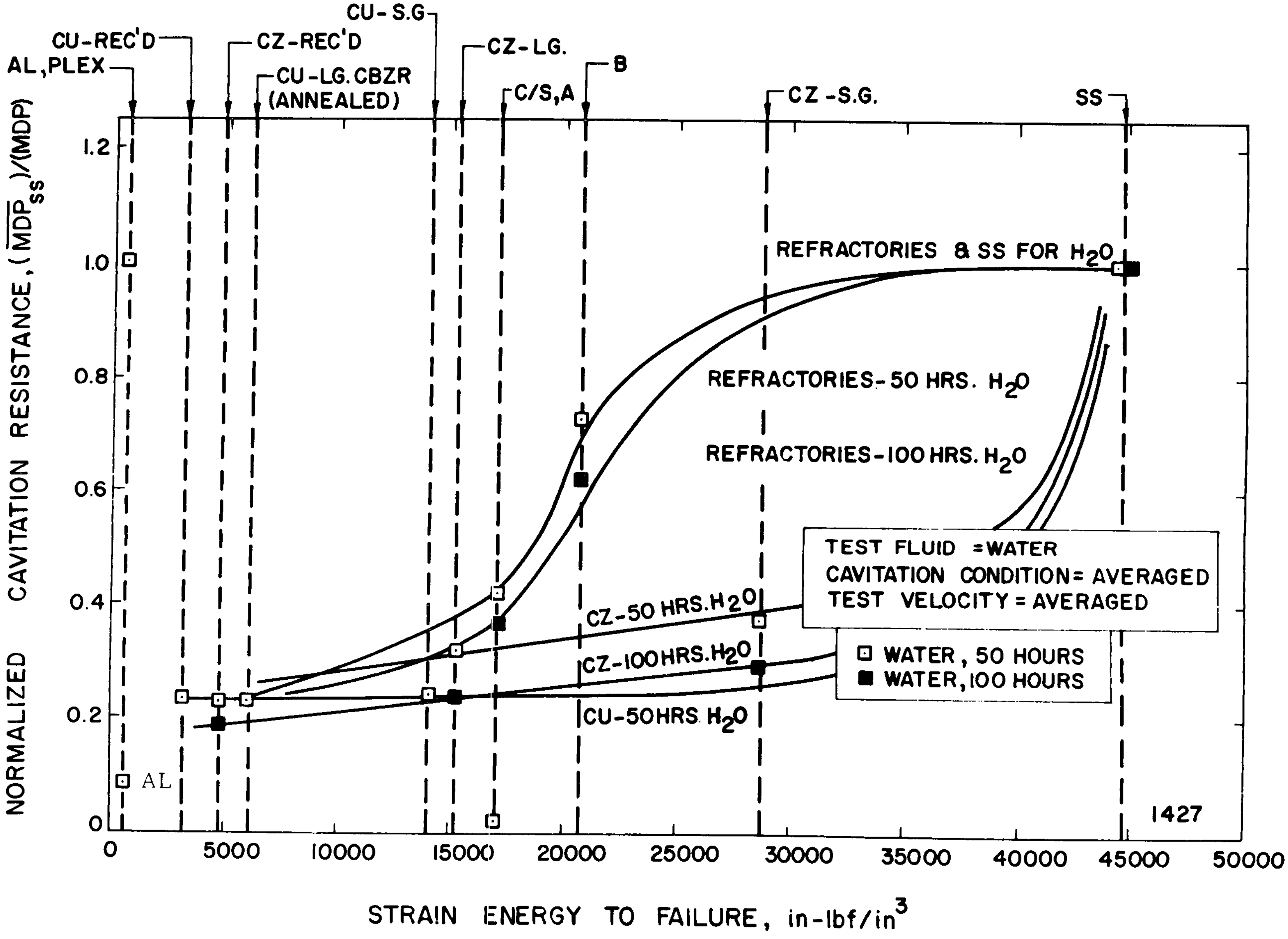


FIGURE 20: Cavitation Damage vs. Strain Energy to Failure for Various Combinations of Materials, Cavitations and Velocities in Water

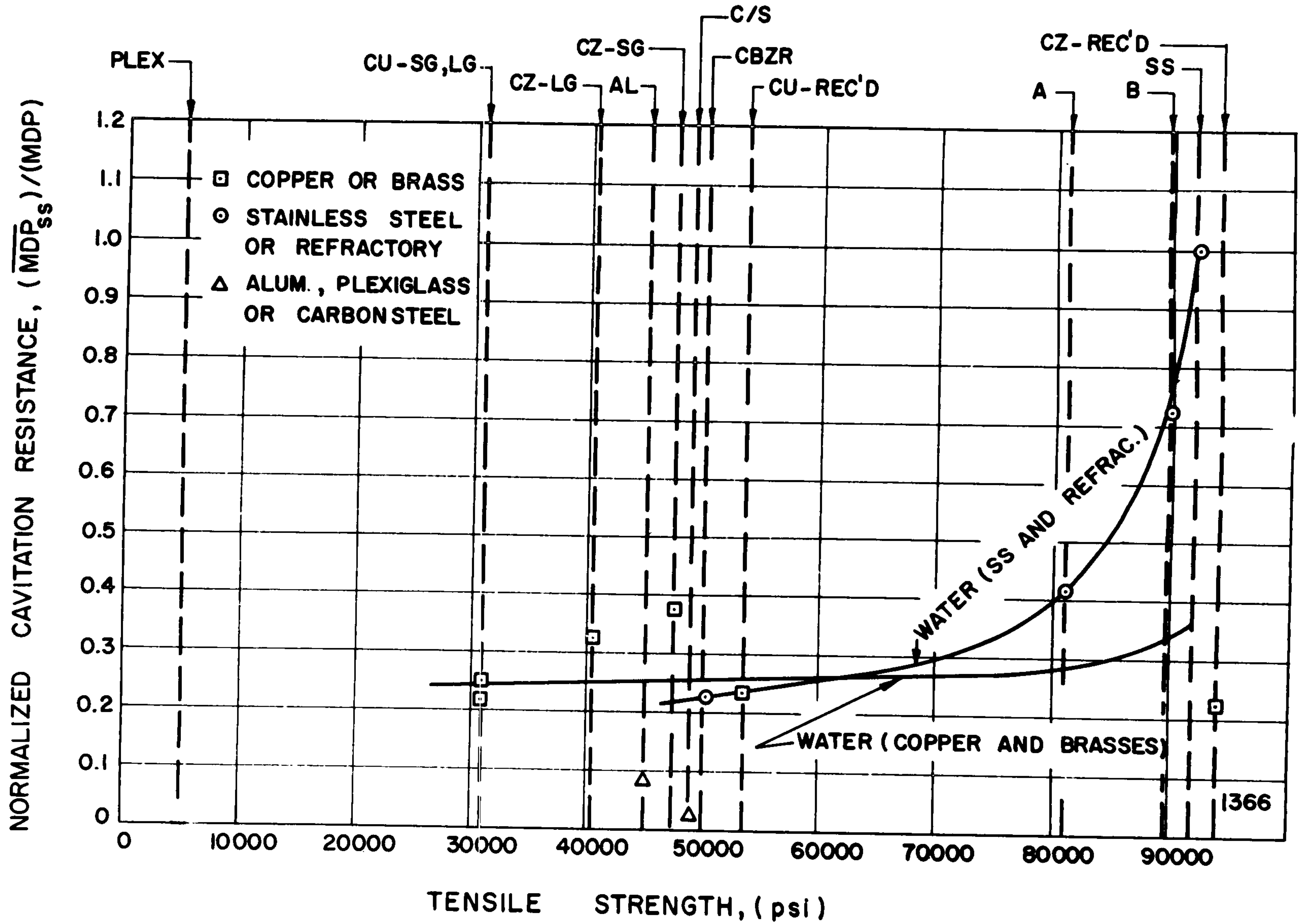


FIGURE 21: Cavitation Damage Versus Tensile Strength for Various Combinations of Materials, Cavitation Conditions and Velocities in Water

The preceeding discussion has neglected fluid-material coupling effects, flow geometry, degree of cavitation, etc., all of which we know to be important. An interesting example of a fluid-material coupling is afforded by plexiglas, which we have found to be comparable to stainless steel in resistence to cavitation damage in water, but very poorly resistent as compared to the metallic materials tested, in mercury. A possible explanation lies in its relatively high strength but very low elastic modulus, allowing it to deflect sufficiently to reduce very localized loads, at least in some cases, to a non-damaging level.

III. CONCLUSIONS

In general it is still not possible to predict cavitation damage to be expected in a prototype machine from laboratory tests. However, progress is being made toward attaining this capability by observing and measuring in laboratory set-ups the effects due to different system variations, and thus obtaining a fuller understanding of the nature of the phenomenon that exists at present. It has become apparent that relatively minor changes in the flow system can create order of magnitude changes in cavitation damage rates. For this reason it is necessary that laboratory tests model prototype systems as closely as possible.

BIBLIOGRAPHY

1. Hammitt, F. G., "Cavitation Damage and Performance Research Facilities", ASME Fluids Engr. Conf., Philadelphia, Pennsylvania, May, 1964, Symposium on Cavitation Research Facilities and Techniques, pp. 175-184.

2. Garcia, R., and Hammitt, F. G., "Ultrasonic-Induced Cavitation in Liquid Metals", to be presented ANS Annual Meeting, and to be published ANS Trans.

3. Knapp, R. T., "Recent Investigations of the Mechanics of Cavitation and Cavitation Damage", Trans. ASME, Vol. 77, 1955, pp. 1045-1054.

4. Knapp, R. T., "Accelerated Field Tests of Cavitation Intensity", Trans. ASME, Vol. 80, No. 1, Jan., 1958, pp. 91-102.

5. Hammitt, F. G., "Observations of Cavitation Damage in a Flowing System", Trans. ASME, J. Basic Engr., Vol. 85, Sept., 1963, pp. 347-359.

6. Hammitt, F. G., et. al., "Initial Phases of Damage to Test Specimens in a Cavitating Venturi as Affected by Fluid and Material Properties and Degree of Cavitation", ASME Paper No. 64 WA/FE-2, to be published Trans. ASME, J. Basic Engr.

7. Varga, J. and Sebestyen, G., "Observations on Cavitation Damage Exponent in a Flowing System", Periodica Polytechnica, Vol. 8, No. 3, 1964, Polytechnical University, Budapest, Hungary

8. Personal Communication from G. M. Wood, Pratt and Whitney Aircraft, CANEL, Middletown, Connecticut.

9. M. Kornfeld and L. Suvorov, "On the Destructive Action of Cavitation" Journal of Applied Physics, Vol. 15, No. 6, 1944, pp. 495-496.

10. Naude, C. F. and Ellis, A. T., "On the Mechanism of Cavitation Damage by Hemispherical Cavities Collapsing in Contact with a Solid Boundary", Trans. ASME, J. Basic Engr., Series D, Vol. 83, No. 4, Dec., 1961.

11. Walsh, W. J., and Hammitt, F. G., "Cavitation and Erosion Damage Measurements with Radio-Isotopes", Nucl. Sci. and Engr., Vol. 14, No. 3, Nov., 1962, pp. 217-223.

12. Hammitt, F. G., et. al., "On Transient Loading Effects in Cavitation Pitting", ASME Paper 63-WA-216.

13. Engel, O. G., "Mechanism of Rain Erosion", Part II, WADC TR 53-192, (Aug., 1953), ASTIA 18703.

14. Engel, O. G., "Erosion Damage to Solids Caused by High-Speed Collision with Rain", J. of Research of Nat'l. Bureau of Standards, Vol. 61, (1958) 47.

15. Hammitt, F. G., Robinson, M. J., Siebert, C. A., and Aydinmakine, F. A., "Cavitation Damage Correlations for Various Fluid-Material Combinations", Department of Nuclear Engineering, Laboratory for Fluid Flow and Heat Transport Phenomena, ORA Report 03424-14-T, University of Michigan

16. Robinson, M. J., "On the Detailed Flow Structure in a Cavitating Venturi and Its Correlation to Cavitation Damage", Ph.D. Thesis, (1965), Department of Nuclear Engineering, University of Michigan, (to be published).

17. Bebchuk, A. S., and Rozenberg, L. D., "The Dependence of Cavitation Erosion on the Solubility of a Gas Above a Liquid", Akusticheskiy Zhurnal, 1960, Vol. 6, No. 4, pp. 498-499.

18. Shal'nev, K. K., "Experimental Study of the Intensity of Erosion due to Cavitation", Cavitation in Hydrodynamics, National Physical Laboratory, Teddington, England, Oct., 1955, 22, p. 1-22, p. 37.

19. Lichtman, J. Z., "Possible Contributions of Reentrant Flow to Cavitation Erosion", ASME Paper 62-HYD-3.

20. Kelly, R. W., et. al., "Rotating Disc Approach for Cavitation Damage Studies in High Temperature Liquid Metal", ASME Paper 63-AHGT-26.

21. Hobbs, J. M., "Problems of Predicting Cavitation Erosion from Accelerated Tests", ASME Paper 61-HYD-19.

22. Barinka, L. L., et. al., "Cavitation Damage Tests of Stressed Specimens with Mercury in a Venturi", Department of Nuclear Engineering, Laboratory for Fluid Flow and Heat Transport Phenomena, ORA Report No. 03424-13-T, University of Michigan, March, 1964.

23. Botcher, H. N., "Failure of Metals due to Cavitation Under Experimental Conditions", Trans. ASME, Vol. 58, 1936, pp. 355-360

24. Mouson, J. M., "Pitting Resistence of Metals Under Cavitation Conditions", Trans. ASME, Vol. 59, 1937, pp. 399-408.

25. Nowotny, H., "Werkstoffzerstorung durch Kavitation", Verlag Gimbh, Berlin, NW7, 1942. English translation as ORA Report No. 03424-15-I, Nuclear Engineering Department, University of Michigan, June, 1962.

26. Thiruvengadam, A., "A Unified Theory of Cavitation Damage", Trans. ASME, J. Basic Engr., Vol. 85, Sept., 1963.

27. Shal'nev, K. K., "Scale Effect of Cavitation Eroiion", Zhurnal Prikladnoy Mekhaniki i Teknicheskoy Fiziki, No. 4, 1962, pp. 121-128.